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Design of coupling interface for narrowband Power Line Communication channel characterization

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*Abstract –***The aim of this paper is to propose an adequate design of coupling circuit for narrowband powerline channel (PLC) characterization for frequencies lower than 500 kHz. This interface filters 50/60Hz mains signal while avoiding damages of measurement equipment and/or any connected analog front end for PLC signal transmission. An experimental characterization setup is also described. Simulated and experimental results for different load conditions are performed for transmission and reception direction showing a small attenuation less than 1 dB for load impedances higher than 10Ω.**

I. INTRODUCTION

Power lines, mainly dedicated and optimized for delivering electricity, are used to transfer data. Although, PLC channel behavior is difficult to characterize since it is a harsh medium, time-varying and impaired by complex noise scenarios, its low cost and wide coverage makes it one of the pivotal technologies in building up smart communication. Therefore, characterizing power line network has been the interest of several research works [1][2][3] and has raised great effort to focus and enhance overall performances even for critical links. Some researchers and industrials have focused on modulation techniques and spread-spectrum techniques in order to cope with fluctuating channel conditions. Another approach is based on controlling and conditioning power-line impedance either by blocking off harsh loads [4] or diminishing switching loads impact [5]. Experimental measurement is also an approach leading to statistical modeling of channel parameters or definition of deterministic mathematical expression for given powerline conditions. Modeling PLC channel can follow either a top down or a bottom-up approach [3]. The former handles the power line channel as a black box and returns an analytical expression of its response by fitting results from measurements. It is adapted for broadband PLC for frequencies higher than 1MHz. As far as narrowband channel in CENELEC [6]/FCC bands (up to 500 kHz) are concerned, multipath expression is not adequate and cannot be directly applied and bottom up approach is preferred as it has no applicability constraints in terms of frequency [3]. Based on power cables physical characteristics, bottom up approach modeling can be verified by measurement on sample PLC networks and after that extended to a more complicated network. For this purpose, an effective coupling interface is required operating on the frequency range from 40 kHz to 500 kHz. The design of such circuit should allow PLC attenuation characteristics extraction in the band of interest and protect measurement instrumentation from 50Hz/220V damages.

In this paper, authors provide a design for narrowband PLC coupling interface taking into account protective measures. Section II gives an overview of PLC attenuation and existent noise scenario. Section III presents design steps and choice for realization of measurement coupling circuit in the band of interest. Section IV is devoted for circuit transfer function and input impedance simulations in transmission and reception path. Experimental results for proposed coupling interface characterization are also provided with different conditions.

II. PLC CHANNEL OVERVIEW

Power line communication channel characteristics vary with frequency, location, time and type of connected equipment making it a harsh medium for communication. In this section, authors present main PLC attenuation characteristics as well as its related noise.

A. Attenuation in PLC

Power cables have a strong low pass characteristic depending on the type of cable, its length and signal frequency. It is mainly caused by dielectric losses in the insulation of the cable and affects the propagation on power line networks. Besides, due to various cable types in existing installation and variation of connected loads, the PLC signal propagation path is subject to multiple reflections caused by network access impedance changes. In [7], access impedance measurements in indoor environment from 50 kHz to 500 KHz shows that its modulus value varies from 1Ω to 60 Ω.

B. Noise in PLC

In addition to attenuation, power lines do not represent a simple additive white Gaussian noise channel; the interference scenario is rather complicated. A large part of this interference is caused by electric machinery and devices during normal operation. In addition, there are many different narrow voltages or current peaks due to a wide range of switching events. PLC noise sources mainly include background and impulsive components occurring periodically, synchronous to mains signal, or aperiodically in single pulses or bursts with short duration from few microseconds to milliseconds. Background noise is generally cyclostationary [8] and its power spectral density decreases as the frequency rises and can be assimilated to a white noise at higher frequencies [9]. The critical noise is the impulsive one. In fact, it occurs shortly but can reach beyond 2kV which is not only deteriorates communication quality but also endangers used circuitry and equipments.

In order to compute a realistic PLC channel transfer function helping in designing appropriate communication systems, few modeling efforts are performed for narrowband PLC compared with broadband (>1MHz).Therefore, authors focus on measuring powerline attenuation for frequencies up to 500 kHz to get a comprehensive behavior. For secure and reliable measurement, a specific coupling circuit is required.

III. MEASUEREMENT COUPLING INTERFACE DESIGN

Performing measurement on power line requires an appropriate coupling interface which is the basis of any powerline modem [9]. It has two fundamental functions: preventing mains high voltage from altering connected equipment and/or low voltage modem circuit; and coupling PLC modem signal with AC mains. A simplified circuit design is shown in Fig.1. Z_{module} and Z_{line} refer to measurement equipment impedance and variable powerline impedance, respectively.
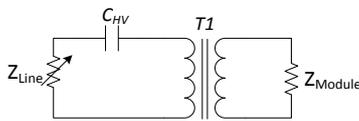

Fig. 1. Coupling interface circuit.

In this section, authors details coupling interface design steps and justify component choices compatible with target application.

A. High pass filtering

In order to avoid low frequencies impairments in narrowband power line communication and very low impedance of mains access, an appropriate design of transmission devices result only above frequencies of 20

kHz [9] .As a first step in coupling operation to the mains, a high pass filter is required to make sure that mains voltage and important part of its harmonics are kept away from measurement instrumentation. For this purpose, a capacitor is placed before transformer satisfying two major points : it should be a high voltage capacitor (C_{HV}) rated to 230/115V(50Hz/60Hz) and having a nominal value meeting powerline applications requirements in terms of maximum reactive power (VA_{max}) limit [9]. According to (Eq.1), for 230 V/50 Hz application with a limit VA_{max} of 10VA, $C_{HV} \approx 601$ nF.

$$C_{HV} = \frac{VA_{max}}{2\pi f \times VAC^2} \qquad \text{Eq.1}$$

To guarantee, a low loss factor associated to capacitor dielectric leading to minimal self-heating, a 330nF metallized propylene film capacitor is used which is suitable for electromagnetic interference suppression and "accross-the line" application avoiding electric shock danger in case of capacitor failure.

B. Coupling transformer choice

For powerline coupling, a galvanic separation in the form of transformer is suitable [8]. An appropriate choice of such transformer *T1* provide a compromise between strong coupling in the transmitter side to reach network without signal amplitude attenuation and weak coupling in the receiver side to filter interferences as much as possible. Care should be taken in dimensioning its winding inductance as well as its leakage inductance to get an effective coupling interface [5]. In fact, the high voltage capacitor in conjunction with transformer's series leakage inductance L_L creates a resonant a series-resonant band-pass filter at frequencies close to the series resonant point (Eq.2). A simplified representation of coupling circuit approximating complex impedance Z_{module} and Z_{line} by real impedances R_{module} and R_{line} is shown in Fig.2.

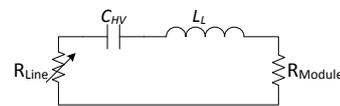$$f_{res} = \frac{1}{2\pi\sqrt{L_L C_{HV}}} \qquad \text{Eq.2}$$

Fig. 2. Simplified equivalent coupling circuit.

The frequency bandwidth is determined by low and high cut-off frequencies at -3dB attenuation respectively f_{low} and f_{high} in (Eq.3). R refers to terminating resistance (R_{line}) in transmitter path from measurement instrument to mains and in receiver path from mains to instrument (R_{module}).

$$f_{low} = \frac{1}{2\pi RC}$$
$$f_{high} = \frac{R}{2\pi L_L} \qquad \text{Eq.3}$$

This simplified model in Fig.2 is only valid for low frequency close to resonant point f_{res}. A more realistic model of coupling interface includes transformer magnetizing inductance L_M in parallel to R_{Module}. According to [5], voltage transfer function in receiving path (from mains to coupling interface) is given as follows in (Eq.4).

$$TF_{Rx} = \frac{(2\pi f)^2 RC_{HV} L_M}{(2\pi f)^3 RL_L L_M + (2\pi f)^2 RC_{HV}(L_L + L_M) + 2\pi f L_M + R} \quad \text{Eq.4}$$

As authors are interested in narrowband powerline from 40 kHz to 500 kHz frequency range, it is better to get a homogenous flat transfer function response in this band of interest and avoid selective resonant behavior in a given frequency. Regarding computation of expected bandwidth of coupling transformer, safety factor need to be included because fluctuation of the terminating power line loads impacts proportionally on the upper and lower cut-off points. For measuring powerline channel frequency response, main characteristics of selected transformer T1 are recapitulated in Table1.

Table 1. Transformer characteristics.

Parameter	Value
Turns ratio N1:N2:N3	1:1:2
Frequency range	10kHz to 10MHz
Primary inductance	0.7mH
Leakage inductance	<0.1µH

C. Protection circuitry

Power line channel are rude operating environment for electrical connected electrical component as presented in section II. There is always a threat coming from fast transients that usually damage transmitter/receiver stages and even connected equipment if not properly protected. Harmful surges can be generated by either special events on network such as lighting, inductive switching... or insulation fault in electrical installation. Therefore, a major step in designing coupling interface for powerline channel response measurement is the implementation of protection stage clamping as much as possible from current and voltage surges. Authors propose to put two protection stage: one stage composed of metal-oxide varistor (MOV) before high voltage capacitor and directly connected to mains and a second stage of suppressor diodes (TVS diodes), placed on the transformer secondary part as shown in Fig.3.The role of MOV is to keep analog stage out over-current transients. It has a high resistance until its triggering voltage is exceeded. Once this voltage level has been exceeded, the MOV decreases its resistance and absorbs the energy from the pulse protecting coupling stage from deterioration. A 420VAC working voltage MOV is selected supporting peak transient current of 4.5kA and capable of absorbing
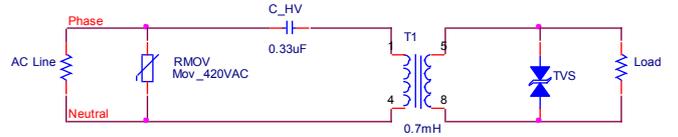
energy of 130J.

Fig. 3. Complete Powerline coupling interface with protection circuit.

On the isolated stage, bidirectional TVS diodes are deployed for their capability in clamping detected overvoltage. In fact, if transmitted or received voltage exceeds its break down voltage it rapidly decreases its impedance and shunts current to the ground. The chosen TVS breakdown voltage is 6.5V.

IV. DESIGN SIMULATION AND EXPERIMENTAL VALIDATION

In this section, authors focus, first, on presenting simulation result of proposed coupling interface then shows characterization measurements of realized circuit prototypes. Circuit frequency response in the band of interest will be evaluated to be taken into account for calibration purpose by cancelling its effect during real powerline measurements.

A. Coupling interface circuit Simulation

Designed coupling circuit in Fig.3 is simulated in both transmitter and receiver path for different mains impedance to extract its behavior in various conditions. For realistic simulation, a 1µH series transformer leakage inductance L_L is added in simulated circuit. A wide band pass characteristic from ~10 kHz to 10MHz is exhibited in Fig.4. For 50Ω power line impedance, according to (Eq.3), low cut-off and high cut-off frequencies are respectively estimated to f_{low} = 9.64 kHz f_{high} = 7.95 MHz which is verified by simulation in Fig.4.
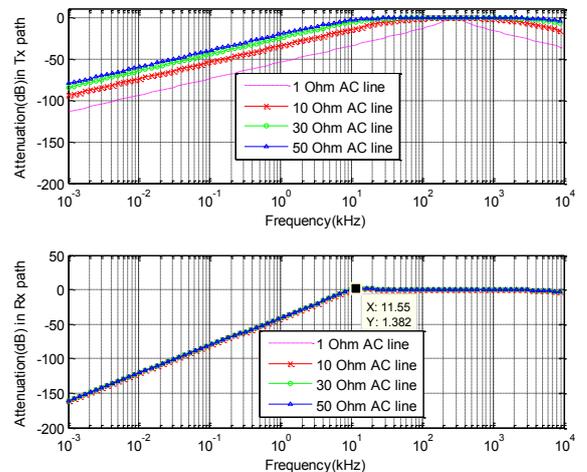

Fig. 4. Simulated coupling circuit transfer function

Regarding rejection of mains signal 50Hz is ensured up to -40dB in transmission direction from analog front end (AFE) to AC line and -90 dB in reception direction from AC line to AFE. According to [10], the low voltage distribution PLC channel impedance is variable going from 1Ω up to 60 Ω for frequencies up to 500 kHz. It fluctuates between 1 Ω and 20 Ω in CENELEC band [3 kHz..150 kHz] and, for upper frequencies till 500 kHz it varies between 10 Ω and 60 Ω. Therefore, the proposed coupling circuit input impedance $|Z_{in}|$ is simulated for different loads values approximating the AC line impedance as depicted in Fig.5. Starting from 40 kHz, input impedance is almost constant and follows the value of connected loads.
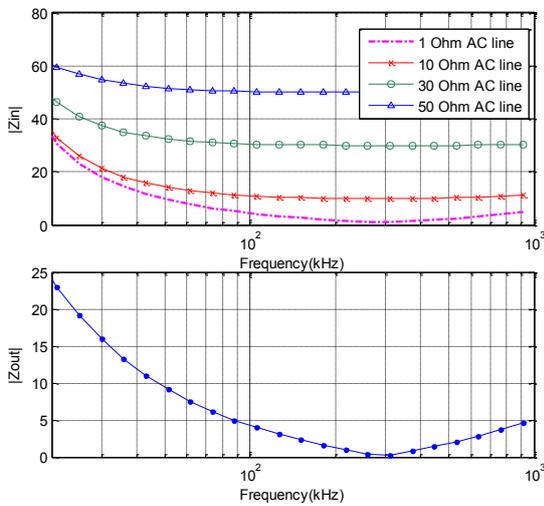
Fig. 5. Simulated coupling circuit input/output impedance.

The output impedance $|Z_{out}|$ is also simulated showing a variation from 12 Ω to 1 Ω in the band of interest from 40 kHz up to 500 kHz. Getting low output impedance near to AC lines one will help to transfer as much as possible signal power in PLC network for transfer function characterization.

B. Characterization Setup

For experimental characterization, authors have prepared two coupling interface prototypes. A spectrum analyzer Agilent E4404B was deployed providing a measurement tool that allows transfer function characterization. It is capable of generating a wideband signal from 9 kHz up to 3.7 GHz at its output port adapted to 50 Ω impedance and retrieve transferred signal via coupling circuit at its input for spectral analysis as illustrated in Fig.6. A reference signal of 3dBm amplitude is injected. To get accurate measurement in characterizing coupling circuit, spectrum analyzer impact has to be estimated to be further cancelled. First, a calibration is performed then; a capture of internal

spectrum analyzer transfer function applied to a reference signal is stored. The latter is obtained by directly looping its output to input port.
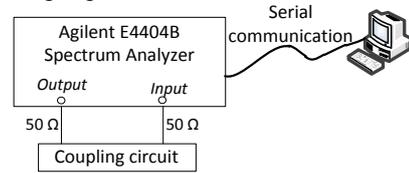

Fig. 6. Characterization Setup for frequencies >9 kHz.

Because of spectrum analyzer frequency limitation (only starts from 9 kHz), it was not possible to verify low frequency attenuation near to mains signal 50Hz/60Hz. Therefore, a gain tracking approach is used based on digital oscilloscope. As illustrated in Fig.7, a sinusoidal signal is generated at a given frequency with a step of 100 Hz in [0.1 kHz, 1 kHz] band and a step of 0.5 kHz in the band [1 kHz, 10 kHz]. This signal is fed to coupling circuit input in both transmission and reception paths. The output is then probed and measured.
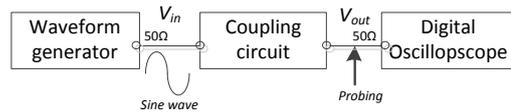

Fig. 7. Characterization Setup for frequencies <9 kHz.

The ratio between injected signal voltage V_{in} and measured voltage V_{out} (V_{out}/V_{in}) gives the coupling circuit attenuation in Fig.8. Because of oscilloscope resolution, this method is applied for frequencies starting from 200 Hz to 10 kHz to get reliable values. For frequencies lower than 200 Hz, real output voltage cannot be detected, it is governed by the oscilloscope noise floor.

C. Experimental Validation Result

In this section, experimental characterization is given within different configurations using a single coupling interface and both interfaces combined one is acting at transmission side, the other at reception side.

1) Single coupling interface

Attenuation measurement is performed according to the two invoked methods using spectrum analyzer and oscilloscope in both directions as shown in Fig.8 and Fig.9. The cut-off frequencies f_{low} and f_{high} are slightly different from theoretical values under the assumption of a 50 Ω AC line. The effective measured values are f_{low} = 5.7 kHz and f_{high} = 2.5 MHz. This deviation may come from the response of used discrete components and the effect of protection circuitry including active component (TVS diodes) which is not taken into account in simulation. The coupling interface presents a flat response in the band of interest with attenuation less than 1dB. It is also noticed that both directions (transmission and reception) exhibit a similar attenuation variation

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which give a symmetric behavior for coupling interface. For infield PLC channel measurement, the transfer function of transmitter path and reception path have to be cancelled from measurements to keep only the effective PLC channel attenuation.
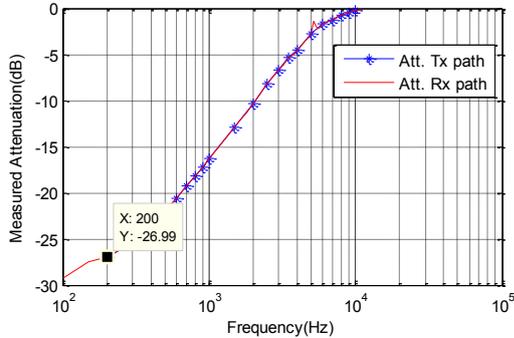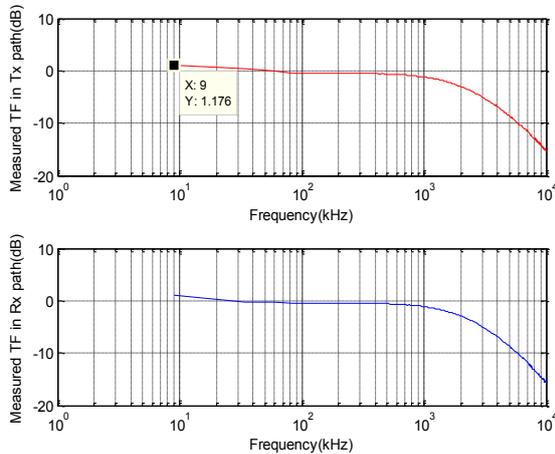

Fig.8. Attenuation results for frequencies <9 kHz.

Fig.9. Attenuation results for frequencies >9 kHz.

2) Combined coupling interfaces

At a first stage, linear behavior is verified when having linear load variation. Both prepared interfaces are loaded with different resistances as in Fig.10. The obtained transfer functions (TF) are reported in Fig.11.
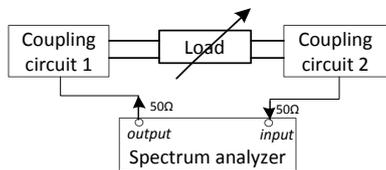

Fig.10. Fixed loads measurement Setup.

The measured attenuation for the three different configurations (with no intermediate load, 1Ω load and 5Ω load) almost exhibits a constant difference for frequencies in between 40 kHz and 500 kHz. At a second stage, the same setup is powered by 220V and used for getting an example of a PLC network response as in Fig.12.
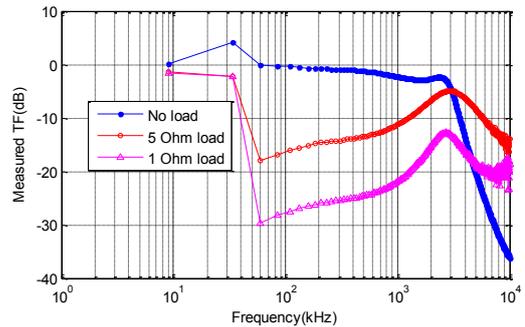

Fig.11. Fixed load measured attenuation.

For this purpose, two measurements are performed. The first acquisition is done when coupling interfaces are plugged on the same point. The second acquisition is done between two distant points (~2m). A spectrum analyzer is also powered near to reception coupling interface. In Fig.13, observed PLC channel transfer function is presented. It shows that signal attenuation over the power line vary from 1 dB to 35 dB within frequencies between 40 kHz and 500 kHz. The fact of increasing distance increases attenuation with up to 10 dB around 400 kHz and 500 kHz. The appearance of notches at certain frequencies, 300 kHz and 800 kHz, results from connected loads; in this case, it comes from adding spectrum analyzer on one plug.
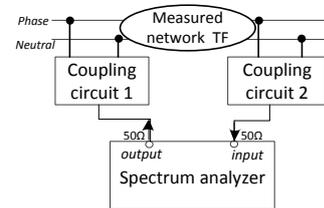

Fig.12. PLC network TF measurement setup.
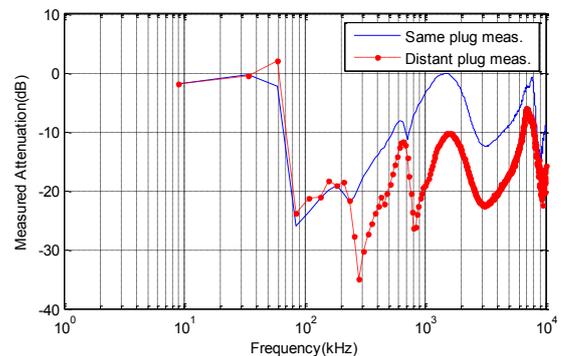

Fig.13. Example of measured PLC network TF.

V. CONCLUSION

In this paper, authors have introduced a design of coupling interface circuit for measuring narrowband PLC channel transfer function. Different components selection

is justified and tuned for required application. Regarding protective measures, two-stage approach is used: overcurrent protection on primary stage based on metal oxide varistor and an overvoltage/overcurrent protection on secondary stage near to measurement instrumentation. Proposed design was simulated and two prototypes were realized to be experimentally characterized in terms of transfer function. Wideband characterization was performed from low frequencies near to mains signal 50Hz to 10MHz. Small attenuation less than 1dB was measured in band of interest till 500 kHz. Immunity test against PLC surges are not performed. But, provided protection circuitry is tuned to allow clamping transient current peaks up to 4.5 kA and voltage is blocked to a break down voltage of 6.5V. Eventually, provided platform helps in estimating PLC channel transfer function with the objective to embed it on a PLC channel emulation platform.

REFERENCES

[1]   Olaf G. Hooijen, "A channel Model for the Residential Power circuit used as a digital communications Medium", IEEE Trans. on Electromagnetic Compatibility, VOL. 40, NO. 4, Nov. 1998.

[2]   M.Zimmermann and K.dostert, "A multipath model for the powerline channel", IEEE Trans. on Communication, VOL. 50, NO. 4, Apr. 2002.

[3]   S. Souissi Ons Benrhouma and Chiheb Rebai, "Bottom Up approach for narrowband Powerline channel Modeling", IEEE GLOBECOM 2013.

[4]   P.A.Brown,"Directional coupling of high Directional coupling of high frequency signals onto power networks," in Proc. 1st Int. Symp. Power-Line Comm., 1997.

[5]   Petrus A. Janse van Rensburg, and Hendrik C. Ferreira, "Dual Coupler for dedicated switching with loads", ISPLC 2007.

[6]   CENELEC EN 50065-1: "Signaling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz, Part I: General requirements, frequency bands and electromagnetic disturbances".

[7]   J.Bausch,   T.Kistner,   M.Babic,   K.Dostert, "Characteristics of Indoor Power Line Channels in the Frequency Range 50-500 kHz", ISPLC, 2006.

[8]   Marcel Nassar, Anand Dabak, Il Han Kim Tarkesh Pandeand Brian L. Evans,"Cyclostationary Noise Modeling in Narrowband Powerline Communication for Smart Grid Applications", ICASSP, 2012.

[9]   Klaus   Dostert,   "Powerline   Communications", Prectice Hall PTR, 2001.

[10]   Martin Sigle, Wenqing Liu, and Klaus Dostert, "On the Impedance of the Low-Voltage Distribution Grid at Frequencies Up to 500 kHz", ISPLC, 2012.